Revista Tecnologia e Sociedade
ISSN: 1984-3526

https://periodicos.utfpr.edu.br/rts

Waste-to-energy: a study applied in a manufacturing industry

ABSTRACT

The aim of this article is to analyze the energy recovery potential from flour-based waste generated in the production process of a manufacturing industry, to promote circular economy and energy sustainability. The study addresses the Sustainable Development Goals (SDGs) 7 (affordable and clean energy), 9 (industry, innovation, and infrastructure), 11 (sustainable cities and communities), and 13 (climate action). The methodology consisted of the collection, preparation, thermogravimetric and differential thermal analysis (TG-DTA), and calorific value estimation of the waste samples. As a result, the useful calorific value (UCV) was estimated at 3,300,600.0 kJ per month, equivalent to commercial firewood. In conclusion, the flour-based waste produced by the analyzed industry exhibits highly favorable characteristics for use as fuel (low moisture content, high organic and volatile material content).

KEYWORDS: Sustainable energy. Industrial waste. Environmental sciences. Circular economy. Organic waste.

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INTRODUCTION

In recent years, the Brazilian electricity sector has been heavily impacted by the water stress experienced by hydroelectric plants. As a result, in 2021, the National Electric Energy Agency (ANEEL) released a new tariff for energy generation, called the "water scarcity flag", with the objective of facing the worst crisis in the country's water reservoirs, in 91 years old. In this scenario, an increase of R$ 14.20 will be applied for each 100 kWh consumed, whenever the “water scarcity flag” is activated. This represents an accumulated increase of 127% in the energy tariff in the period from July to September 2021 (CNN-Brasil, 2021). In May 2024, the Brazilian hydrological scenario became favorable again, and ANEEL announced a reduction of around 37% in the value of the yellow flag and 31.1% in the ref flag (ANEEL, 2024). This shows the large fluctuation in the value of electrical energy.

The crisis in the electricity sector, in turn, brings huge losses to the national economy, directly affecting the performance of the agro-industrial sectors, with an increase in the operating cost, and compromising the population’s income and quality of life. Therefore, a country’s economic and social development can be measured in terms of its ability to meet domestic energy demand at an affordable cost (Jasiunas and Mikkola, 2021; Brambilla and Mueller, 2004).

The term “sustainable energy” may be defined as to ensure energy for the multiples demands considering the environmental limits (Holden, Linnerud and Rygg, 2021). It has been widely used in the scientific literature to address the relationship between energy demand and supply, and it rests on three pillars: (1) efficiency, (2) accessibility, and (3) diversification (Jasiunas and Mikkola, 2021; Rosen, 2021). The first two dimensions seek to promote the optimization of customer service, that is, to guarantee the supply of energy with the highest quality at an affordable cost, while the third dimension (diversification) seeks to encourage the expansion of the possibilities of energy sources, considering whether the availability of resources and technologies in the region (Geng and Evans, 2022; Soares and Cândido, 2019).

The diversification of the energy matrix has intensified in recent years with the expansion of distributed generation practices, with application in, for example, small generators, photovoltaic panels, and small hydroelectric plants (INEE, 2021). Allied to this, the recovery of energy available in by-products from production processes stands out (Sonsale, Yashpal and Pohekar, 2021). This strategy simultaneously integrates sustainable energy and circularity of production.

The aim of this article is to analyze the potential for energy recovery from organic waste (biomass) generated by the machine performance tests in a manufacturing industrial plant. The study focuses on the themes "energy" and "waste", contemplated by the objectives (7) clean and accessible energy, (9) industry, innovation, and infrastructure, (11) sustainable cities and communities, and (13) action against global climate change, from the 2030 Agenda of the United Nations (ONU-BRASIL, 2021).

This topic aligns with the journal's editorial line, as it demonstrates the contribution of scientific research to the development of new technologies that integrate social, economic, and environmental aspects for positive impacting in contemporary society and future generations. We can highlight, for example, other studies published recently by this journal about it, as Mulinari and Bilotta (2024), and Poyer et al (2024).

Energy, waste, climate change and industries

The latest report by the Energy Research Company (EPE), of the Ministry of Mines and Energy, shows that the industrial segment is responsible for the consumption of 44.5% of the entire national demand for fuel (transport and machinery) and 41.9% of the electricity generated in the country (EPE, 2020). The annual increase in the industrial energy consumption rate in the international scenario is 0.9% (IEA, 2020). However, the Brazilian industry also accumulates great potential opportunities for energy efficiency and security, through technological innovation (CNI, 2019). Therefore, the recovery of energy in the industrial sector can bring positive impacts in facing the water shortage that affects the water reservoirs of the country's hydroelectric plants.

On the national scene, the sector also stands out for solid waste generated, both in production processes and in its facilities. According to data from a study carried out by the Institute for Applied Economic Research, in Brazil, 97,655,438 tons of industrial waste were produced in 2007, of which 96.1% were classified as non-hazardous. This information was obtained from the extinct network of the Integrated Waste Exchange System, which had the participation of industry federations and sectorial associations in the country (IPEA, 2012).

According to the National Solid Waste Policy (Law 12,305/2010), the management and disposal of industrial waste is the responsibility of the generating agent (polluter pays principle) and, therefore, it bears the high operating costs with treatment, transport, and final disposal of waste. On the other hand, this policy also encourages the recovery and energy use of industrial waste, as a mechanism to promote sustainable development and business competitiveness (Brasil, 2010), by reducing energy consumption and promoting energy efficiency in the sector (Geng and Evans, 2022), in face to the uncertainty demand and supply (Fazlollahtabar, 2025).

For example, use of cotton/polyester waste torrefaction to produce biochar in textile industry – a carbon rich material produced from the burning of organic matter (Aljomah et al., 2025), conversion of filter cake in pellets as fuel for electricity generation in sugar industry (Pajampa et al., 2024), beneficiation of sludge waste from paper industry to produce biomethane, biohydrogen, bioethanol, biobutanol, and biodiesel (Kumar and Verma, 2024), and food wastes from hotel industry for briquette, biogas, syngas and biochar production (Muchele et al., 2025).

Thus, in this context, the recovery of energy from by-products of the production process emerges as an environmentally sustainable (appropriate management) and economically attractive (avoided cost) alternative for the disposal of non-recyclable waste (Sonsale, Yashpal and Pohekar, 2021).

Allied to this, the Greenhouse Gas Emission and Removal Estimation System (SEEG), an initiative of the Climate Observatory, accounted the national emission at 2.16 Gton CO_2 for the year 2020. This represents an accumulated increase of 18.9% the Brazilian emission of greenhouse gases (GHGs) in the last 10 years. The energy, industrial processes, and waste sectors together account for 27.11% of the country's total emissions. The goal of the Nationally Determined Contribution (NDC), presented by the Brazilian government at the 26th United Nations Conference on Climate Change (COP), is to cut 50% of national emissions by 2030, compared to 2005. Among the actions Proposals to reach this level are the expansion of renewable energy sources in the composition of the national energy matrix (by 45 to 50%) (Calzolari, Genovese and Brint, 2021). In this sense, the implementation of energy recovery technologies in the production process can add efforts for Brazil to reach its NDC goal.

In the industrial sector, measures to achieve the NDC include, for example, technological updating (more efficient processes), rational use of natural resources (reduction of input consumption), production line management and planning (waste minimization), recovery materials and energy from by-products (circular economy), innovation in the design of new products (investment in Research and Development - R&D) (Sonsale, Yashpal and Pohekar, 2021; Calzolari, Genovese and Brint, 2021; Soh and Wong, 2021). These strategies promote the implementation of a low carbon economy, as they encourage the circularity of production and encourage the transition from non-renewable energy sources to renewable sources.

The sectoral plan for the consolidation of the low-carbon economy in the Brazilian transformation industry, called “Industry Plan”, is one of the instruments of the National Policy on Climate Change (Low 12187/2009) for reducing GHG emissions and reaching the NDC goals. The five acting axes of the Industry Plan are: carbon management; recycling and co-processing; voluntary mitigation actions; low carbon technologies; and energy efficiency and cogeneration (Mistage-Henríquez and Bilotta, 2016).

In the same context, an international example is Green Britain Department for Business, that considers possible to reduce 4 $MtCO_2$ by 20250 if national industries adopt alternatives to heat waste recovery, and energy efficiency practices (Geng and Evans, 2022).

Sustainable energy in the industrial sector

Goal 7 of the UN's 2030 Agenda establishes the presupposition of “guaranteeing access to affordable, reliable, sustainable and modern energy for all” (ONU-Brasil, 2021). This declaration, in turn, guides the understanding that the concept of sustainable energy is based on the three pillars of sustainable development (environmental, social, and economic dimensions), with an increasingly relevant role on the international agenda (Gunnarsdottir et al., 2021).

The industrial sector, without a doubt, has great potential for the implementation of sustainable energy, whether through investment in energy use efficiency (technological updating and qualification of labor) or in energy recovery (heat and electricity) from the waste (by-products) generated in the production line (Sonsale, Yashpal and Pohekar, 2021).

Geng and Evas (2024) classified the research about energy in industries in 4 main classes (benchmarking, energy analysis, bolilers, and efficiency), by bibliometric network, and highlighted that adopting zero energy waste goal encourage the continuous improving process in the sector.

Transforming by-products into energy (waste-to-energy) is a sustainable strategy to manage organic waste, as it is an economically attractive solution (minimization of disposal operating costs), environmentally sustainable (reduction in the exploitation of sources of origin fossil fuel) and socially favorable (increased energy supply to serve domestic users) (Geng and Evans, 2022). In this sense, waste incineration is a widely used technique. It consists of burning dry material, in a controlled and oxygen-saturated environment, to ensure complete combustion and maximum efficiency (Gil, 2022).

The calorific value (amount of energy released on combustion) varies over a wide spectrum of intensity, depending on the physical and chemical characteristics of the incinerated material (Sonsale, Yashpal and Pohekar, 2021). Table 1 shows examples of heat capacity of some fuels.

Table 1 – Comparison between the calorific value of some fuels.

Fuel	Higher Calorific Power (kcal.kg^{-1})
anhydrous ethyl alcohol	7,090.0
Sugarcane bagasse	2,257.0
Charcoal	6,800.0
commercial firewood	3,300.0
Diesel oil	10,750.0
Waste from paper industry [1]	4,776.9

[1] Average value. Source: Sonsale et al. (2021), EPE (2019).

The incineration is considered a type of thermochemical treatment of waste, in which the organic matter is oxidized to simple gases (CO_2, H_2, volatile organic compounds, etc.) and ash, by the presence of oxygen and under high temperature (~550ºC), to achieve maximum performance. The heat released from the reaction, in turn, can be recovered and used to generate thermal and electrical energy (Gil, 2022; Carneiro et al., 2020).

Several studies published in recent years have reported the remarkable installed capacity for energy generation in industrial plants using different types of waste. For example, Coimbra et al. (2015) reported the potential to supply 3,926.62 kcal.kg^{-1} of secondary sludge (10 wt%) from the biological treatment of effluent from a pulp and paper industry. Dong and Lee (2009) found that solid waste produced by the industrial sector of a large city in Korea (paper, wood, rubber, plastic, resin, and sludge) can generate 16,459.75 kcal.kg^{-1}.d^{-1} for the municipality. Mulinari and Bilotta (2024) estimated that it is possible to recover 7,091.18 kcal.d^{-1} with the biogas produced by an industrial plant during the sewage treatment of around 242 thousand inhabitants of the city of Curitiba.

According to a survey carried out by Gil (2022), on the Scopus platform, between 2015 and 2020, 3,075 works were published resulting from research on energy recovery processes from biomass of different origins and purposes, and 364 articles on biomass and incineration, combustion, and pyrolysis. This demonstrates the importance of this research in the current context. Currently, the biomass generated by the industry analyzed in this study is destinated to landfill, for lack of information about solutions with potential to be implemented into manufacturing industry. It shows the originality and applicability of this paper.

In this context, this research provides subsidies to support the company's decision-making on more sustainable solutions. The waste analyzed in this work is periodically produced by the company in performance tests, and its current destination is industrial landfill.

METODOLOGY

This research was carried out with a large manufacturing industry located in the city of Curitiba, southern Brazil. The company manufactures various types of equipment to meet the national demand of the food industries, and a series of performance tests is done with each machine before shipping them to the customers. For these tests, the company uses a flour (organic powder), which contains an average composition of 72.0% carbohydrates, 9.8% protein, 1.4% total fat, and 3.2% dietary fiber (5.4% of moisture). This waste (called biomass or organic waste) has high percentage of carbon, and, for this raison, it was considered as a potential waste-to-energy to be analyzed. The average quantity of biomass produced by test is 2,920 kg year^{-1}.

Sample preparation

100 g of biomass (organic waste) was collected daily for 5 days in a container positioned after the company's testing phase and carried to the chemical analysis laboratory. The material was homogenized with a mechanical stirrer, divided into 5 portions, then 10 g of each of them was taken and macerated vigorously in a porcelain crucible to ensure sample uniformity. After that, the determination of the total solids content (TS) in the homogenized sample was carried out, using the method described by (APHA, 2005).

Thermogravimetric analysis and differential thermal analysis (TG-DTA)

TG-DTA curves were generated from the analysis of the homogenized sample of farinaceous residue (~12.0 mg) in an alumina crucible, using the DTG-60 equipment (Shimadzu, Japan). The heating rate applied was 10oC min^{-1}, starting from room temperature (~20ºC) until reaching 600ºC, in a synthetic air environment to ensure complete combustion of the sample, with a feed flow of 50 mL.min^{-1}. The DTG-60 equipment was previously calibrated with calcium oxalate monohydrate standard and the sample mass loss (%) over time was determined by the TA-60 WS software.

Estimate of energy potential

The superior calorific value (SCV), the inferior calorific value (ICV) and the useful calorific value (UCV) of the biomass sample were estimated by the method proposed by Parikh et al. (2005) (equations 1 to 3). The amounts (%) of moisture (U), volatile material (MV), organic material (MO) and ash (A) in the sample were determined by TG-DTA curves. The masses (%) of carbon (C), fixed carbon (CF), hydrogen (H) and oxygen (O) were calculated using the method described by Parikh et al. (2005) (equations 4 to 7).

$$\mathrm{SCV} = (84.5104\ \mathrm{CF}) + (37.2601\ \mathrm{MV}) - (1.8642\ \mathrm{A}) \qquad (1)$$

$$\mathrm{ICV} = (\mathrm{SCV} - 540\ \mathrm{H}) \qquad (2)$$

$$\mathrm{UCV} = [(\mathrm{ICV}.(1 - (0.01\ \mathrm{U})) - (6\ \mathrm{U})] \qquad (3)$$

$$\mathrm{FC} = (100\% - \mathrm{MV} - \mathrm{A} - \mathrm{U}) \qquad (4)$$

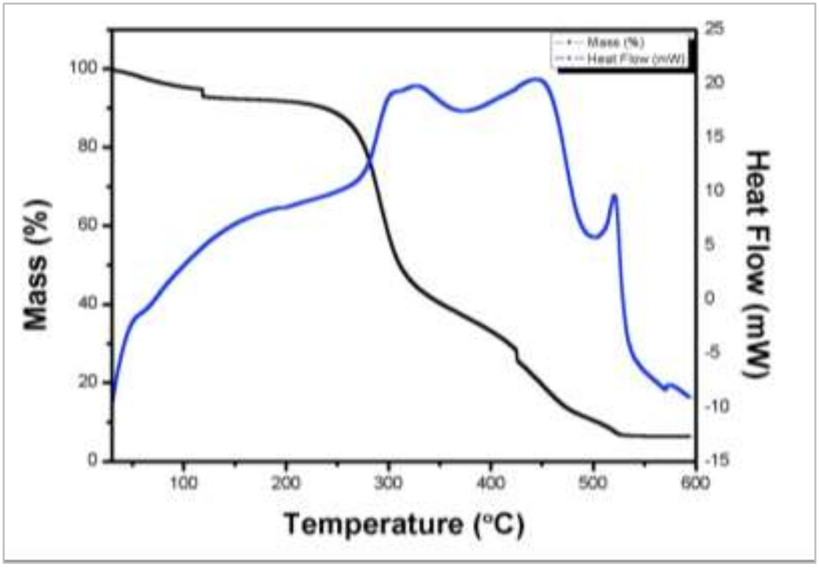
$$C = 0.637\,CF + 0.455\,MV \qquad (5)$$
$$H = 0.052\,CF + 0.062\,MV \qquad (6)$$
$$O = 0.304\,CF + 0.476\,MV \qquad (7)$$

RESULTS AND DISCUSSION

TG-DTA and DSC analysis

Figure 1 shows the TG-DTA curve resulting from the combustion of the sample in a controlled environment. The result of the thermogravimetric analysis revealed a low percentage (by mass) of moisture (9.9%) and ash (5.6%) and a high percentage of volatile material (84.5%).

Figure 1.TG-DTA and DSC curve of the analyzed residue.



TG-DTA analysis is used to determine the amount of organic matter and ash in a material, which is measured by the variation in the sample mass during combustion. The DTG-60 equipment internally has a high-precision balance that detects the slightest change in the sample's mass over time and transmits this information to the computer connected to it, which records the behavior of the residue graphically, in the form of a TG curve (Carneiro et al., 2020). The analysis is divided into 3 main phases: (i) up to ~100°C moisture evaporates; (ii) between ~100 and 600ºC, organic matter, carbon and volatile compounds are released; (iii) above ~600°C only the remaining ash from combustion remains (Qi et al., 2017). Table 2 summarizes the TG results.

Table 2. TG results.

Step	Δm (%)	ΔT (oC)
1 st	5.41	30.00 – 123.37
2 nd	35.39	123.37 – 324.68
3 rd	15.64	324.68 – 435.15

The first inflection of the curve (Figure 1) appears at ~130°C (baseline 1). Up to this point, there is a loss of mass due to evaporation of the water present in the sample and after that the mass stabilization is verified up to ~220ºC. Depending on the type of bond between the water molecules and the particles that make up the solid, the removal of water can happen close to 100°C (free water) or above that temperature (bound water) (Wu et al., 2020).

Between ~220 and ~550ºC there are two new inflections in the TG-DTA curve (Figure 1). This second phase is marked by the loss of mass due to the release of volatile compounds, which represent 84.5% (by mass) of the analyzed sample. The inflection detected at ~320ºC may indicate the detachment of organic compounds and the oxidation of fixed carbon with lower activation energy, as they occur at a lower temperature (baseline 2). The inflection recorded at ~550ºC reveals that a new level of mass stabilization has been reached (baseline 3). Therefore, in this phase there is the complete release of organic compounds. The resulting mass at ~550ºC will be ash (residual inert material) (Yaashikaa et al., 2022).

Energy recovery potential: analysis

Table 3 presents the result of the estimation of the calorific value of the residue. The thermogravimetric analysis showed that the sample has very favorable characteristics for its use as fuel, mainly the low moisture content (U) and the high content of organic material (MO) and volatile (MV). These two parameters define the power recovery intensity (UCV). The moisture present in the sample interferes with the ICV value, as the water evaporation phase (Figure 1) is an endothermic process, which involves the consumption of energy to promote a change in physical state (liquid-vapor). On the other hand, the volatilization phase of organic compounds is an exothermic process, with release of chemical energy (stored inter and intramolecularly) during combustion.

Table 3. Results of energy potential calculations.

Parameter	Variable	Value
Mass content (%) Values obtained by TG-DTA	Moisture (U)	9.9
	Volatile material (MV)	84.5
	Ashes (A)	5.6
Mass content (%) Values calculated	C	44.8
	H	5.8
	O	43.2
	Others	6.3
Mass content (%) Values calculated	Fixed carbon (CF)	9.9
	Organic material (MO)	94.4
Calorific Power (kcal kg-^{1}) Values calculated	Superior (SCV)	3,974.7
	Inferior (ICV)	3,664.0
	Useful (UCV) [1]	3,241.9

[1] Equivalent to 13,572.8 kJ kg^{-1}.

The methodology proposed by Parikh et al. (2005) to estimate the superior, inferior, and useful calorific value of a sample has been accepted by the scientific community for the reliability of the results (Carneiro et al., 2020; Malucelli et al., 2020). Considering that the average monthly production of farinaceous residue in the industry is ~243 kg, there is a potential to generate 788,862.33 kcal month^{-1} (9,466,348.00 kcal year^{-1}) of thermal energy. The analyzed sample presented SCV of 3,974.7 kcal kg^{-1} and this value is higher than commercial firewood (3,300.0 kcal kg^{-1}), according to data reported by (EPE, 2019).

Incineration is the most common method of burning biomass and the main technologies are turbines, boilers, and electric ovens. Electricity generation from biomass is an expanding possibility, although the conversion efficiency, in this case, is much lower (20 to 40%) when compared to the heat production yield (~80%) (Yaashikaa et al., 2022).

In 2019, the European Commission announced the “Green Agreement” (EGD). The purpose of this commitment is to direct investments towards green and sustainable technological solutions, aimed at new businesses, and make Europe the first “climate-neutral” continent by 2050. And, in this sense, the practice of generating energy using waste from biomass (waste-to-energy) comes aligned to this action (Gil, 2022).

According to European regulation, biomass residues are not considered hazardous, as they do not have an explosive, oxidizing, flammable, irritating (to skin and eyes), toxic, or carcinogenic character (Gil, 2022). In Brazil, the NBR 10.004 standard establishes that hazardous waste is those that are flammable, corrosive, reactive, toxic, or pathogenic (ABNT, 2004). Therefore, biomass residues can be sent to incinerators and other energy recovery technologies, as they do not qualify as hazardous.

Obtain energy from biomass waste is an example of circular economy strategy, which results in positive impact into the environment (less raw material is extracted from the nature, pollution and contamination of water, soil, and air is reduced, higher maintenance and preservation of green areas and their ecosystems), the society (higher life quality and human health), and the economy (new business opportunities, lower operating cost with waste treatment and destination, and investment recovery). Public policies are strongly necessary to regulate circular economy in the industrial sector, and support differentiated lines of credit to make its implementation feasible. These aspects are linked with five objectives of Sustainable Development Goals (SDG) established by the 2030 Agenda of the United Nations: ODS 7) clean and accessible energy; ODS 9) industry, innovation, and infrastructure; ODS 11) sustainable cities and community; ODS 12) responsible consume and production; ODS 13) actions against global climate change.

For the application of this study to other industrial plants, it is necessary to previously evaluate: (i) the amount of organic waste generated (scale dependency); (ii) the physicochemical characteristics of the waste (which significantly influence SCV, ICV, and UCV values); (iii) the trade-offs relationship (i.e., the impact of pollution caused by the technology in relation to the amount of energy produced); (iv) the implementation of an energy efficiency policy in the company; and (v) its economic feasibility (including in comparison with other technological alternatives, such as biogas generation).

In many cases, the economic aspect can be a significant barrier to implementing energy efficiency measures in an industry’s production process, due to the high cost of upgrading equipment. As an alternative, international support can enable the transition to a low-carbon economy and more sustainable practices (Poyer et al, 2024).

For future studies are recommend: i) a differential scanning calorimetry (DSC) step to explain the mass loss at the time; ii) tests with calorimetric bomb in laboratory to get experimentally the value of superior, inferior, and useful calorific power; iii) a comparison between theoretical and empirical results for the SCV, ICV, and UCV; iv) a modeling study of the theoretical and empirical results; and (v) an economical study about it implementation and operational feasibility (CAPEX and OPEX).

CONCLUSION

The industrial sector is responsible for the growing demand for energy and solid waste generation. Sustainable energy and circularity of production are intended to promote more efficient solutions in production processes. The recovery of energy stored in by-products from industrial activities (waste-to-energy) meets these two principles. This strategy is innovative in the management of organic waste, as it is an economically attractive solution (minimization of operating costs with disposal), environmentally sustainable (reduction in the exploitation of fossil sources) and socially favorable (increase in energy supply to serve domestic users).

The farinaceous residue resulting from the production process of the manufacturing industry studied had a higher calorific value of 3.974.7 kcal kg^{-1}, counting the potential for generating 788.862.3 kcal month^{-1} of thermal energy with the incineration technology. Furthermore, thermogravimetric analysis and differential thermal analysis revealed that the residue has low moisture content and high content of organic and volatile matter.

As findings of this study, it is highlighted that the analyzed waste showed potential to be used as fuel by the industrial plant studied, in terms of both the quantity of waste generated and its physicochemical characteristics.

Waste-to-energy: um estudo aplicado em uma indústria de transformação

RESUMO

O objetivo deste artigo é analisar o potencial de recuperação de energia a partir de resíduos farináceos do processo de produção de uma indústria manufatureira, para promover a economia circular e sustentável sustentabilidade energética. O estudo contempla os Objetivos de Desenvolvimento Sustentável (ODS) 7 (energia limpa e acessível), 9 (indústria, inovação e infraestrutura), 11 (cidades e comunidades sustentáveis) e 13 (ação contra a mudança global do clima). A metodologia consistiu na coleta, preparação, análise termogravimétrica e diferencial térmica (TG-DTA) e estimativa do valor calórico de amostras dos resíduos. Como resultado, o valor calorífico útil (VCU) foi estimado em 3.300.600,0 kJ por mês, equivalente a lenha comercial. Como conclusão, o resíduo farináceo gerado pela indústria analisada possui características muito favoráveis para seu uso como combustível (baixo teor de umidade, alto teor de material orgânico e volátil).

PALAVRAS-CHAVE: Sustentabilidade energética. Resíduos industriais. Ciências ambientais. Economia circular. Resíduos orgânicos.

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Recebido: 27/09/2024
Aprovado: 27/03/2026
DOI: 10.3895/rts.v23n69.19226

Como citar:

COELI, Caio; CARVALHO FILHO, Marco Aurélio da Silva; BILOTTA, Patricia. Waste-to-energy: um estudo aplicado em uma indústria de transformação. **Rev. Tecnol. Soc.**, Curitiba, v. 23, n. 69, p.256-270, abr./jun, 2026. Disponível em:

https://periodicos.utfpr.edu.br/rts/article/view/19226

Acesso em: XXX.

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